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Regional Hydrogeology of the Athabasca Oil Sands Area, Alberta

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ABSTRACT

Regional features of the groundwater flow systems of an area of about 20,000 sq mi (52,000 sq km) in northeastern Alberta are discussed. Depths of investigation range from 1,000 to 4,000 ft (305 to 1,220 m) and include rock units of Holocene, Pleistocene, Cretaceous and Devonian ages. Data sources included observation wells and conventional drillstem tests.

Alternating zones of relatively high and low permeability within the glacial and Cretaceous rock units combine with locally great topographic relief to produce unusual groundwater flow conditions. Unsaturated conditions extend into deeply buried rock units miles from their outcrop and result in a complicated pattern of saturated and unsaturated zones when viewed in cross section.

Groundwater in the Devonian Methy, McLean River and La Loche Formations is characteristically confined by the Prairie Evaporite and has freshwater heads up to several thousand feet above the top of the aquifer. Total dissolved solids of water in these units exceeds 400,000 mg/l at certain locations.

Environmental and technical ramifications of the regional hydrogeologic features of the area are discussed. Points of concern include the existence of collapse features and dewatering operations.

INTRODUCTION

The Alberta Research Council began, in 1973, a regional hydrogeological evaluation of the Athabaska Oil Sands Area. The area under study *(Figure 1)* includes all of the Athabasca Oil Sands and encompasses the area from Tps 77 through 100 and Rs 1 through 25 W 4th Mer. This constitutes an area of about 20,000 sq mi (52,000 km²).

The Athabasca Oil Sands ranks as one of the major oil deposits of the world. Government estimates (Alberta Oil and Gas Conservation Board, 1963) place the amount of bitumen in the deposit at 626 billion barrels. Surface mining of the deposit has been taking place at Great Canadian Oil Sands (GCOS) (Tp 92, R 10, W 4th) since 1967 and will commence soon at the Syncrude site (Tp 93, R 10, W 4th).

Both of those plants have encounterel unexpected groundwater conditions: GCOS experienced difficulties related to water in the overburden; Syncrude has been forced to install an extensive dewatering system to lower water pressures at the base of the deposit.

The existence of the problems and the possibility of others led the Alberta Research Council to propose a regional hydrogeological investigation. The philosophy of this project is that an early understanding of the groundwater conditions of the area will allow prior consideration of potential environmental and technical problems related to that resource. The ultimate goal of the Project is an understanding of the regional hydrogeology of the area.

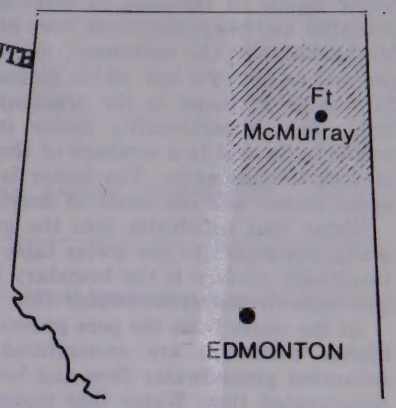


Figure 1. Location of study area.

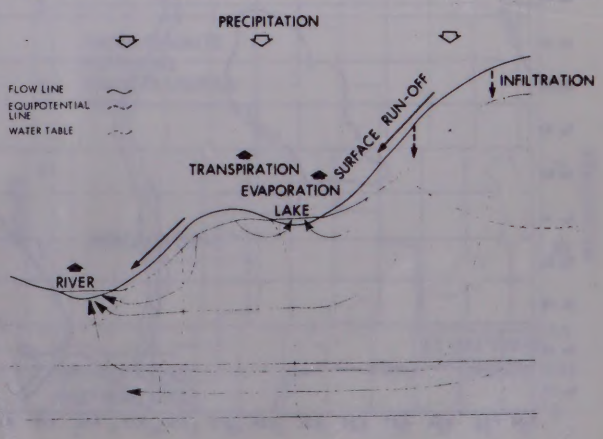
The purpose of this paper is to present an overview of the geology and hydrogeology of the area as well as to discuss environmental and technical concerns related to groundwater. A short summary of current concepts in groundwater geology will precede the actual discussion of the Athabasca Oil Sands Area.

Seventy-five wells of depths up to 1,900 ft (579 m) were installed at 15 locations within the study area. Separate wells of various depths were constructed at each location so that a vertical distribution of groundwater parameters could be sampled. Alberta Research Council (1976, 1977) produced a series of publications presenting the basic data of this network. Included in the publications are site geology, well construction, aquifer test results, water analyses and water level hydrographs.

CONCEPTS IN GROUNDWATER GEOLOGY

A schematic view of the hydrologic cycle is presented in *Figure 2*. The portion of this cycle occurring beneath the land surface is of main, but not sole, concern to the groundwater geologist. The modern groundwater geologist recognizes that all water below the surface of the ground is groundwater, except that which is chemically bonded. It exists to the depth at which all interconnected porosity vanishes. Ground-

Figure 2. The hydrologic cycle.



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water moves in response to differences of hydraulic potential and obeys the three laws of thermodynamics. Mathematically the movement of groundwater is expressed as Darcy's law which states that the rate of flow is proportional to the gradient of the hydraulic head. The proportionality factor is called hydraulic conductivity and is a measure of the ability of a mass of rock to pass water. The factor is actually a second order tensor and has units of length per time.

Water that infiltrates into the ground moves generally downward to the water table *(Figure 2)*. This imaginary surface is the boundary between saturated and unsaturated groundwater flow (Freeze, 1969).

At the water table the pore pressure is atmospheric; higher pressures are encountered on the side of saturated groundwater flow and lower on the side of unsaturated flow. Water that moves through the unsaturated zone, crosses the water table and enters the groundwater flow system is termed groundwater recharge (Freeze, 1969). Water that leaves the groundwater flow system by means of stream baseflow, springs, seepage areas and evapotranspiration is groundwater discharge (Freeze, 1969).

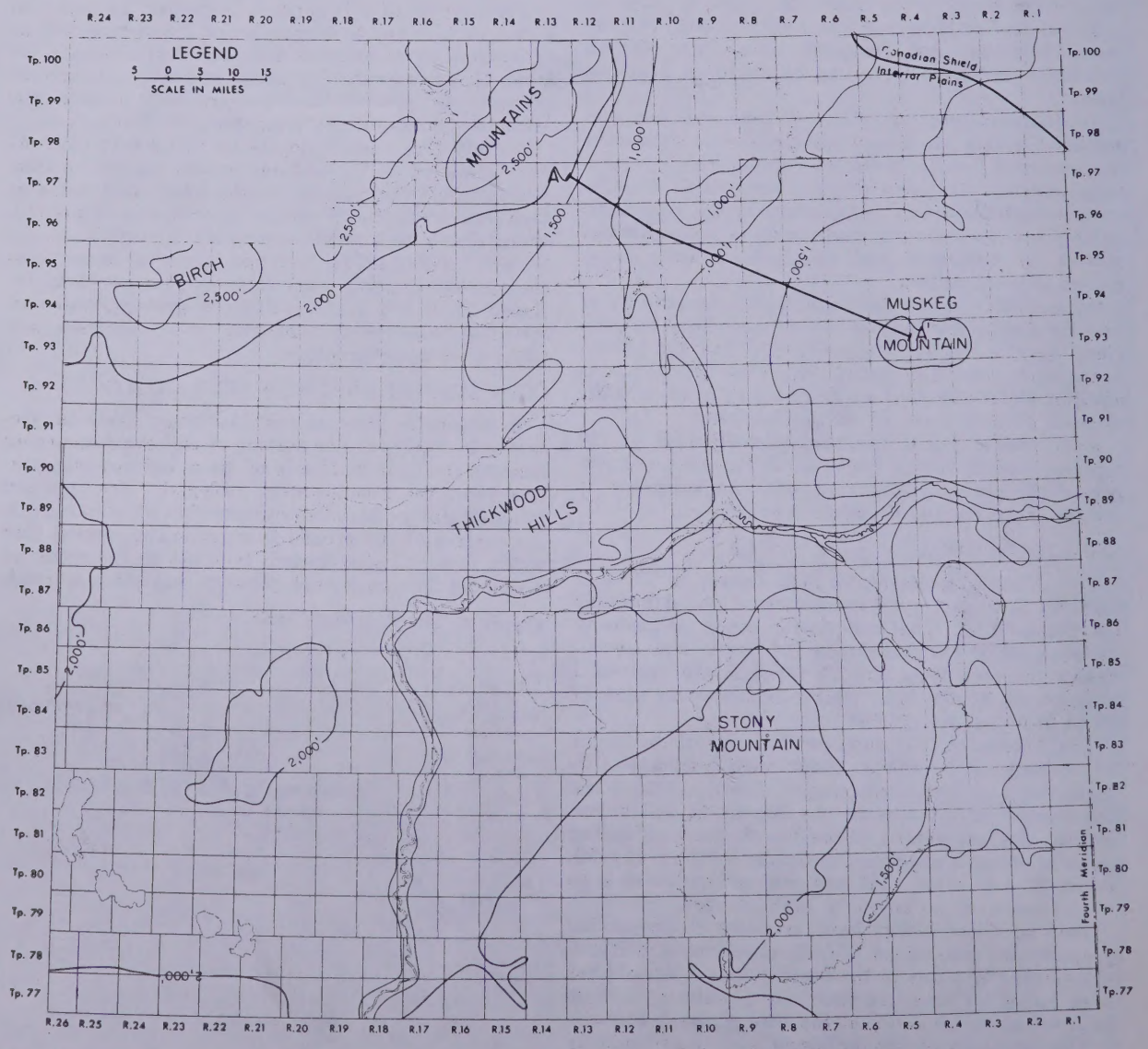
The path of flow of each individual particle of water is called a flow line or streamline (Harr, 1962). When a groundwater flow system is depicted schematically only a few representative flow lines are shown *(Figure 2)*.

The energy or hydraulic head of an individual particle of groundwater at a particular time and place can be expressed as the sum of its elevation head and pressure head. The rate of flow of groundwater is so small that kinetic energy or velocity head is ignored.

An equipotential surface is an imaginary surface connecting locations having equal hydraulic heads at a specified instant in time. Since groundwater flow systems are usually presented diagrammatically on plane surfaces such as maps or cross sections the intersection of this plane with the equipotential surface produces equipotential lines *(Figure 2)*.

The study of the hydrogeology of the Athabasca Oil Sands is a regional groundwater flow analysis — that is, it examines patterns of groundwater flow over large distances and is not concerned with small scale features. The analysis assumes that groundwater conditions in the area are fairly independent of time because they are controlled largely by regional topography and geology — both of which change only very slowly with time. It is reasonable to assume that

Figure 3. Physiography of the Athabasca Oil Sands Area.



the regional groundwater flow systems seen today were in existence at the close of glaciation 10,000 years ago. It has been hypothesized that certain regional groundwater flow patterns observed today may have developed as long ago as the late Tertiary (J. Tóth, Alberta Research Council, pers. comm.) when the basic features of the present landscape were probably being formed.

PHYSIOGRAPHY

Within the region are four major topographically high areas *(Figure 3)*: the Birch Mountains with elevations up to 2,700 ft; Muskeg Mountain with elevations up to 2,000 ft; Stony Mountain which rises to 2,500 ft; Thickwood Hills with elevations exceeding 1,700 ft.

Between these hills is a broad flat plain which slopes gradually towards the major streams and rivers. The Athabasca River is incised several hundred feet into this plain as is its major tributary, the Clearwater River. The hydraulic grade line of other minor tributaries to the Athabasca River usually drops quite rapidly within a few miles of that river producing precipitous gorges. Farther upstream these tributaries are generally slow flowing and meandering.

About 50 percent of the area is covered by organic soil (Lindsay *et al.*, 1958, 1962, 1963), referred to as muskeg. Muskeg exists both on the topographic highs as well as on the gently sloping plains. Muskeg is uncommon on steep slopes but is quite prevalent on gentler slopes. Frost has been noted within the muskegs of the northwest quarter of the map during the summer season (Lindsay *et al.*, 1958, 1962, 1963). Whether this is permafrost or climafrost is not known.

Mineral soils of the western half of the area tend to be Grey Wooded while those of the eastern half tend to be Podzols.

CLIMATE

The area experiences long cold winters and short cool summers. January temperatures average about –22°C while July temperatures average 16°C at Ft. McMurray Airport *(Figure 4)* (A. Mann, Environment Canada, pers. comm.). The mean annual temperature at this location is –0.6°C. Winter temperatures tend to be lower in the river valleys than on the surrounding uplands. The converse is observed for summer temperatures. The area averages less than 100 frost-free days per year (Longley, 1968).

The average annual precipitation at Ft. McMurray Airport is about 432 mm (17 in), slightly over half of this falls as rain during June, July, August and September as shown on *Figure 5*. Snowfall averages about 1,499 mm (59 in) each year and is quite evenly distributed among the winter months.

Bruce and Weisman (1967) show that annual evaporation is expected to be about 381 to 508 mm (15 to 20 in) per year. Potential evapotranspiration *(Figure 5)* exceeds average precipitation from May through August and on an annual basis.

SURFACE WATER

The flow of the Athabasca River is monitored at Athabasca just southwest of the area — at Ft. McMurray and at Embarras — just north of the area. Between 1972 and 1975 the average annual discharge at these locations was 12.2 x 10^6 A-F (acre-feet) (15.1 x 10^9 m^3), 19.15 x 10^6 A-F (23.6 x 10^9 m^3) and 20.06 x 10^6 A-F (24.8 x 10^9 m^3) respectively. (Environment Canada, 1974, 1975, 1976).

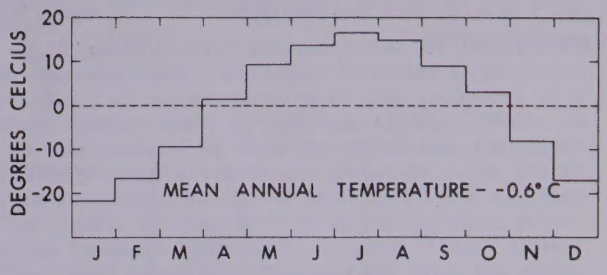


Figure 4. Average annual temperatures at Ft. McMurray Airport.

GEOLOGY

The stratigraphic sequence for the Athabasca Oil Sands Area *(Table 1)* is, in general terms, Cretaceous clastics rocks overlying Devonian carbonates and evaporites. Glacial deposits of Pleistocene age attain thicknesses up to 600 ft (183 m) in the eastern half of the area and are generally less than 100 ft (30 m) thick in the west. Except for very small areas along the Athabasca and Clearwater Rivers *(Figure 6)* rocks of Cretaceous age lie immediately below the glacial drift.

The regional structure of the area is that of a monocline dipping southwestward. The Precambrian surface *(Figure 7)* dips southwest at about 28 ft/mi (5.3 m/km). Two major faults are hypothesized in the Precambrian on the basis of borehole data: one, herein termed the Sewetakun Fault, trends north-south passing under Ft. McMurray and the other runs northwest-southeast. The two faults appear to intersect in the southeastern portion of the area. Displacement on the Sewetakun Fault appears to be 200 to 300 ft on the Precambrian surface.

The surface of the Prairie Evaporite also shows a regional dip to the southwest of about 28 ft/mi (5.3 m/km) *(Figure 8)*. Major depressions on this surface are noted to coincide with the Sewetakun Fault. These are thought to be due to solution of gypsum and salt. Northeast of the 300-foot contour a pronounced levelling out of the surface of the Prairie Evaporite is seen. This is due to solution of the salt since the formation lies quite close to the surface.

The contact between the Devonian limestone and the overlying McMurray Formation is a major unconformity and probably represents several periods

Figure 5. Average monthly precipitation and evapotranspiration at Ft. McMurray Airport.

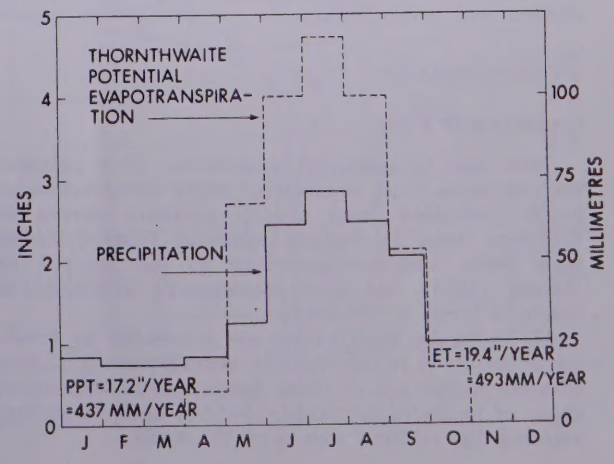


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Table 1. Stratigraphic and hydrostratigraphic sequence.

	System or Series	Rock Unit		Lithology
	Pleistocene and Recent			Glacial till, sand, silt and gravel
		Erosional unconformity		
Cretaceous Hydrostratigraphic Unit	Upper Cretaceous	Smoky Group (K_s)		Shale
		La Biche Formation (K_{lb})		Shale
		Dunvegan Formation (K_d)		Sandstone
		Shaftesbury Formation (K_{sh})		Shale
	Lower Cretaceous	Pelican Formation (K_{pl})		Sandstone
		Joli Fou Formation (K_j)		Shale
		Grand Rapids Formation (K_g)		Lithic sand and sandstone
		Clearwater Formation (K_c)		Shale, siltstone and glauconitic sandstone
		McMurray Formation (K_m)		Quartzose sand impregnated with heavy oil
		Erosional unconformity		
Upper Devonian Hydrostratigraphic Unit (D_{bl}+)	Upper Devonian	Woodbend Group		Limestone reef, shale and shaly limestone
		Beaverhill Lake Formation (D_{bl})		Argillaceous limestone, calcareous shale
		Slave Point Formation		Limestone and dolomite
Middle Devonian Hydrostratigraphic Unit (D_m+)	Middle Devonian	Fort Vermilion Formation	(D_{pe}+)	Anhydrite and dolomite
		Watt Mountain Formation		Shale and anhydrite
		Muskeg Formation		Anhydrite and dolomite
		Prairie Evaporite Formation		Anhydrite and salt
		Methy Formation (Keg River-equivalent)		Reefal dolomite
		McLean River Formation (Chinchaga-equivalent)		Dolomite, claystone and evaporites
		La Loche Formation		Claystone and arkosic sandstone
	Precambrian (P_e)			Metasedimentary rocks and granite

of subaerial erosion (Carrigy, 1959). No rocks of ages between Devonian and Cretaceous have been found in the area. Significant relief is indicated on the pre-Cretaceous erosion surface *(Figure 9)* in the vicinity of the Sewetakun Fault. The closed depression in the north-central area actually has a small central core with an elevation less than 400 ft (122 m). It is apparent that the relief on the post-Paleozoic surface is the result of a combination of subaerial erosion and karstification.

HYDROGEOLOGY

Groundwater Flow

Data used to interpret groundwater flow patterns include heads from observation wells and freshwater heads calculated from shut-in pressure curves of drillstem tests. Formation pressures from drillstem tests were analyzed according to the method of Horner (1951) and were subsequently expressed as heads in terms of freshwater.

All hydraulic head values are presented as freshwater heads. It is felt that the overall picture of flow created by the use of these heads rather than other types of heads (Lusczynski, 1961) is acceptable, considering the regional nature of the study.

The distribution of hydraulic conductivity for various formations is presented in *Figure 10.* The distribution of these values within a stratigraphic unit is log-normal. Highest values are expected in the Grand Rapids Formation in which the median hydraulic conductivity is about 2.8×10^{-4} cm/sec. The median values for the Clearwater and McMurray are 6.2×10^{-6} cm/sec and 1.9×10^{-5} cm/sec respectively. Hydraulic conductivity values are significantly lower in the Devonian units; the Beaverhill Lake and the Middle Devonian Hydrostratigraphic Unit (which consists of Methy, McLean River and La Loche) have median values of 3.2×10^{-7} cm/sec.

It is thus seen that several orders of magnitude differences in hydraulic conductivity exist between the Cretaceous and Devonian units and also among the Cretaceous units themselves. The significance of these contrasts is shown later.

Freshwater equipotential surfaces for the Clearwater, McMurray, Devonian above the Prairie Evaporite and Devonian below the Prairie Evaporite are presented in *Figures 11, 12, 13 and 14.* Highs in the heads occur under Birch Mountain, Muskeg Mountain and Stony Mountain. Groundwater flow in the study area is generally towards the northeast and steeply downward. Hydraulic heads in most units are well below ground surface. Heads at or above ground

level are observed in the Middle Devonian Hydrostratigraphic Unit.

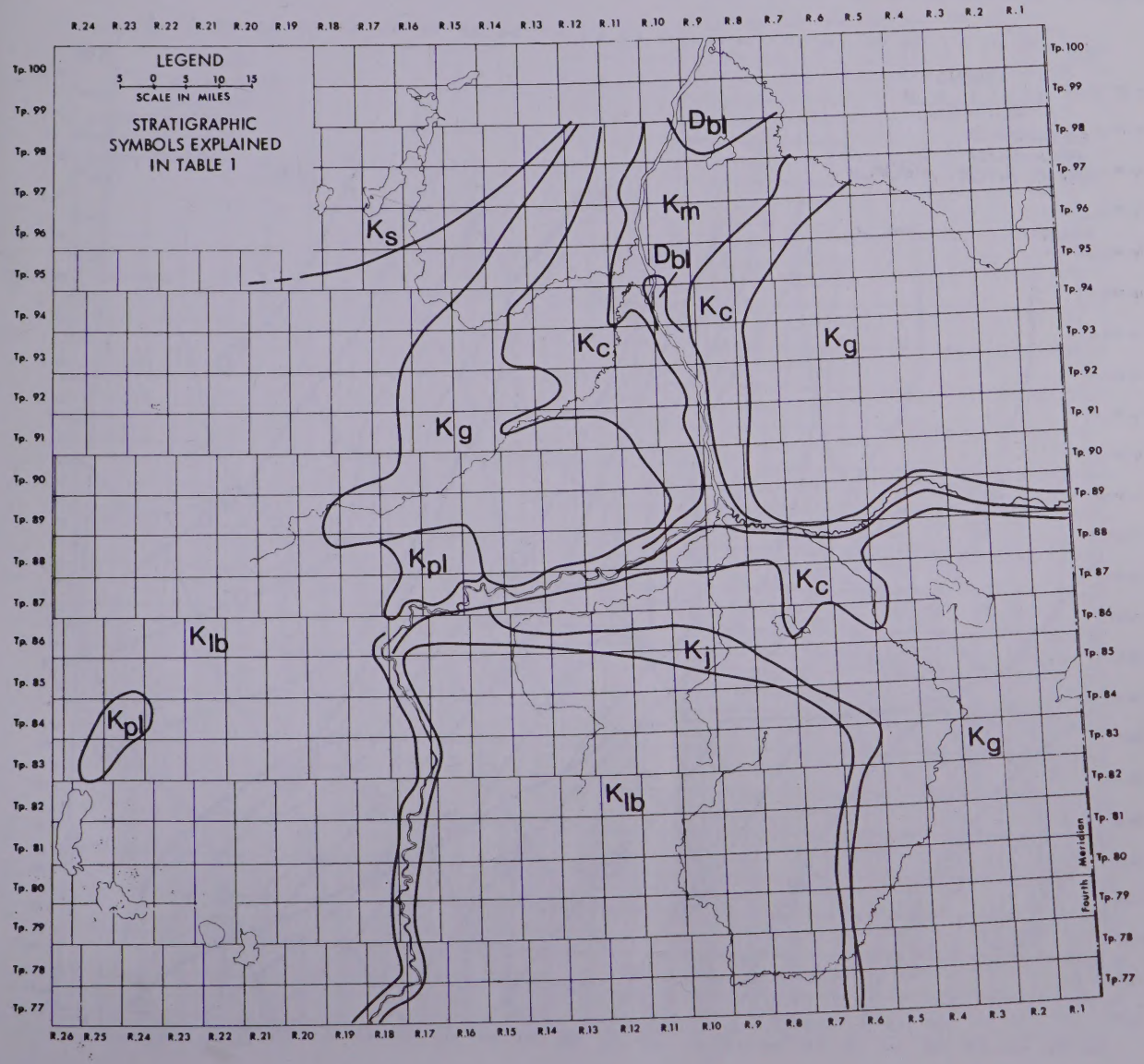
Three hydrostratigraphic units (Maxey, 1964) are identified in the study area *(Table 1)*. These are identified mainly through examination of the hydrogeological cross section *(Figure 15)*. The Cretaceous Hydrostratigraphic Unit consists of the glacial drift and all Cretaceous rock units. It is characterized by zones of strongly vertical groundwater flow interspersed between zones of dominantly lateral flow. The high local relief, combined with strong contrasts in hydraulic conductivity, produce a series of perched conditions which gradually disappear with distance from the subcrop as shown in *Figure 16*.

The Upper Devonian Hydrostratigraphic Unit consists of all Devonian strata above the evaporite deposits of the Ft. Vermilion, Watt Mountain, Muskeg and Prairie Evaporite Formations. This unit is characterized by 1) dominantly horizontal direction of flow (as opposed to the alternating pattern of the overlying Cretaceous), 2) an impermeable base formed by the evaporite and 3) low hydraulic heads along the Sewetakun Fault caused by secondary permeability associated with the collapse of the limestone.

It should be noted at this point that the distribution of hydraulic head in the Upper Devonian Hydrostratigraphic Unit is consistent with that presented at a much smaller scale by Hitchon (1969a, 1969b). It was demonstrated in these two papers that the Upper Devonian and Carboniferous carbonate rocks act as a low-potential drain under most of Alberta and that flow within this unit is towards the northeast corner of the Province. Specifically, Hitchon (1969a) states: "The drain essentially channels flow from the entire Alberta basin and discharges it in the region of the Athabasca oil sands." The low fluid potential of the drain was cited as being caused by highly permeable reef complexes. McCrossan and Glaister (1964) state that the permeability of the Beaverhill Lake Formation in established fields is 12 to 100 millidarcies (1.2×10^{-5} to 1×10^{-4} cm/sec).

The Upper Devonian Hydrostratigraphic Unit (essentially the Beaverhill Lake) is not reef bearing in the study area. The primary hydraulic conductivity and relationship to topography are not adequate to account for extensive lowering of fluid potentials in this unit.

Figure 6. Bedrock geology.

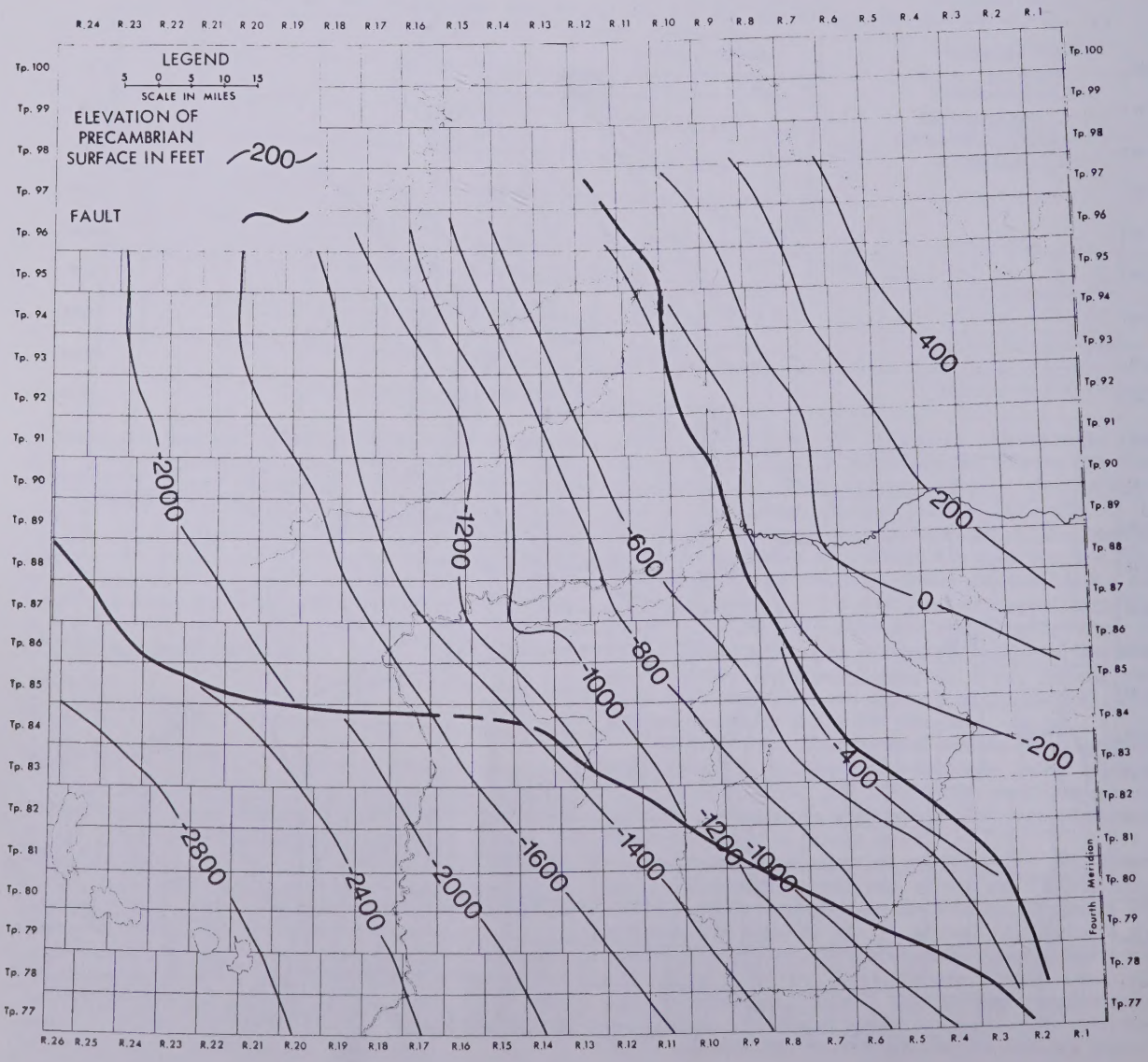


It is hypothesized that the widespread distribution of low heads in the Upper Devonian Hydrostratigraphic Unit is caused by the combination of a major fault and collapse of areas of that unit due to solution of salt. There is strong evidence that the Sewetakun Fault along the Athabasca River is not limited to the Precambrian and that it has influenced rocks as young as Upper Devonian age. This fault acts as a vertical drain lowering the heads in formations adjacent to it to approximately river level. Groundwater from the Beaverhill Lake, Methy, McLean River and La Loche Formations flows upward along the fault zone. This upward flow has enchanced dissolution of the Prairie Evaporite and subsequent collapse of the Beaverhill Lake at, for instance, Bitumount *(Figure 9)*. Collapse of the Beaverhill Lake into solution cavities in the Prairie Evaporite has increased the macroscopic permeability of the limestone in the vicinity of the Athabasca River. This increase in overall permeability has contributed to the spread of the low fluid potential zones in the Upper Devonian Hydrostratigraphic Unit.

The Middle Devonian Hydrostratigraphic Unit consists of all Devonian strata below the evaporite deposits and above the Precambrian. This unit is characterized by 1) confinement by nearly impermeable units both above and below, 2) freshwater heads *(Figure 14)* at or above ground level *(Figure 3)* and 3) total dissolved solids concentrations of 200,000 to 300,000 mg/l.

It should be noted that east of the Athabasca River and north of the Clearwater the criterion for distinction between the two Devonian Hydrostratigraphic Units breaks down. The Methy, McLean River and La Loche Formations, in the absence of the Prairie Evaporite, have a quite different hydrogeologic regime than farther west: they no longer have substantially higher heads than the overlying units *(Figure 15)* and the total dissolved concentration is not expected to exceed 50,000 mg/l. Lateral flow appears to be westward toward the Athabasca River, however, it should be noted that only one data point exists east of the river. Groundwater is postulated to be moving westward from this site toward the river and subsequently upward along the fault. It should be emphasized that the volumes of flow are small because of the probable low hydraulic conductivity. This is substantiated by the observation that major groundwater discharge does not appear to be taking place

Figure 7. Structure on the top of the Precambrian.



along the Athabasca River in the study area.

It is apparent from the preceding discussion that the author does not give special status to the oil sands *vis-a-vis* regional groundwater flow. The heavy oil is considered to act to reduce, but definitely not eliminate hydraulic conductivity. (Hydraulic conductivity of the oil sands is considered to be the permeability of the combined bitumen and sand matrix to water.) It should be pointed out that the above statement is made in the context of a regional hydrogeological study. The rate and pattern of development of regional groundwater flow systems is controlled, by and large, by the rate and pattern of development of the regional topography. Because of this, the time context becomes of major consideration in parameters such as permeability. Permeabilities that might be considered as effectively nil for purposes of well hydraulics are significant in terms of regional groundwater flow systems.

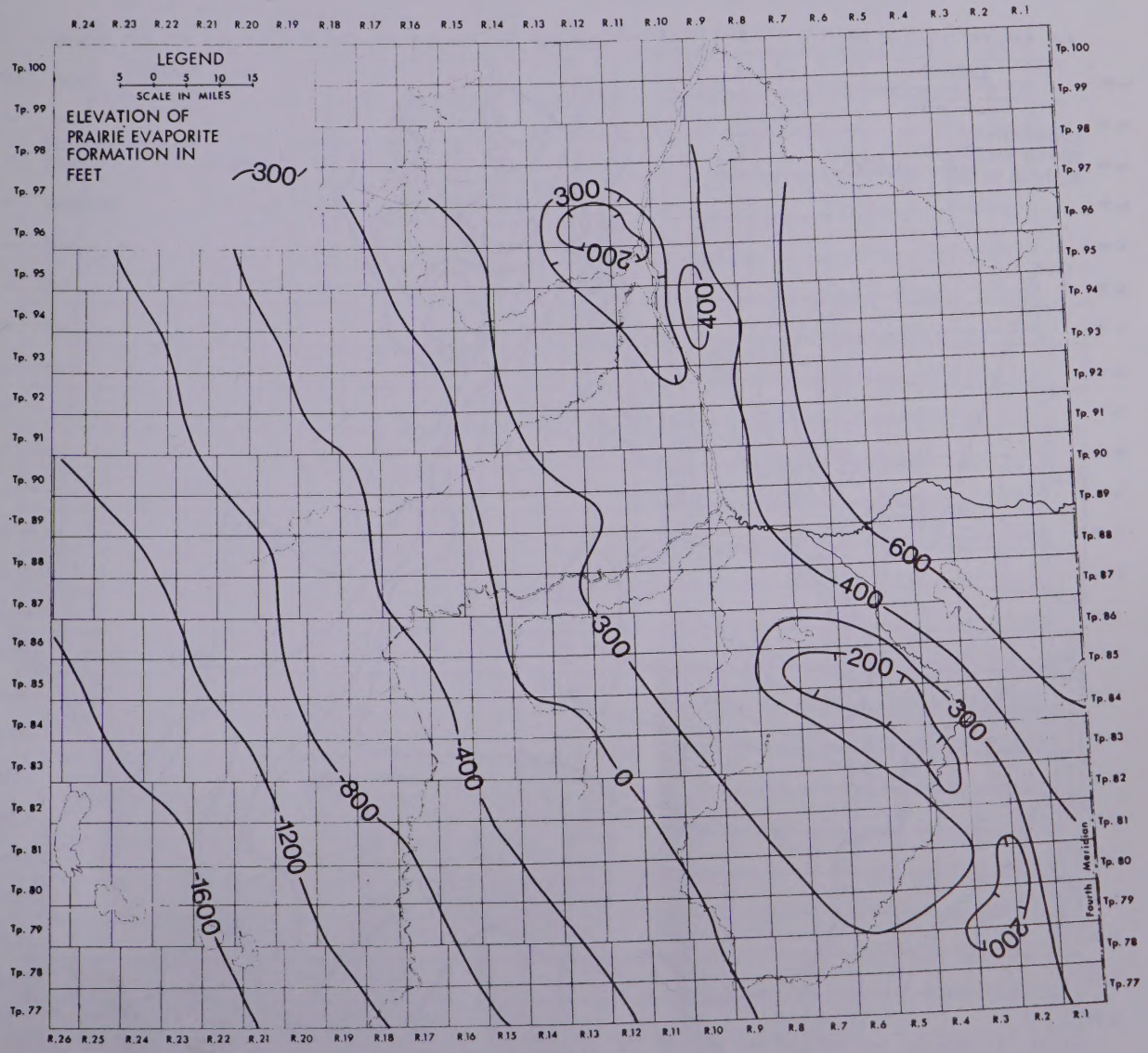
Indirect evidence also exists which indicates that significant regional groundwater flow does take place through the oil sands:

1. Construction of the flow nets for cross sections of the area did not necessitate any special consideration to be made for the McMurray Formation. That is, the data utilized to construct those diagrams did not require the McMurray to be treated differently from other low permeability units.

2. Well number 7-135 is completed in a shaly low-bitumen zone underlying 60 ft (18 m) and overlying 40 ft (12 m) of good quality oil sand. A pumping test revealed an average hydraulic conductivity of about 5×10^{-4} cm/sec. Total dissolved solids of water samples taken annually from this well have been quite stable at about 1000 mg/l. The annual water level hydrograph for this well is of similar character to those of other wells of similar depth elsewhere that are completed in units other than McMurray Formation. This well has no characteristics that distinguish it from other wells in the network that are not completed in McMurray. There is no positive evidence displayed by observations at this well to indicate special conditions within the oil sands themselves.

3. Total dissolved solids in water from the Beaverhill Lake and Woodbend Groups is not expected to exceed 10,000 mg/l over most of the study area. If the McMurray were of extremely low or zero permeability one would anticipate higher concentrations of dissolved constituents.

Figure 8. Structure on the top of the Prairie Evaporite Formation.



ENVIRONMENTAL AND TECHNICAL IMPLICATIONS

Mining Operations

The area currently considered for mining operations (defined here as oil sand overlain by less than 200 ft (61 m) of overburden) is divided into three parts — Muskeg River Area, Ells River Area and Mildred Lake Area *(Figure 17)*. Discussion of environmental and technical implications for each area is made separately.

Muskeg River Area

The major hydrogeological characteristic of this area is the development of the basal McMurray as an excellent aquifer due to a decrease in the oil saturation of that portion of the unit. Intensive networks of dewatering wells are anticipated to be necessary to allow mining of this area, unless current technology changes. Elaborate depressurizing schemes will have to be worked out as an integral part of all stages of mine planning. Dewatering operations in the basal McMurray will cause a large depression in the piezometric surface of that aquifer. It should be expected that water will move both laterally from the McMurray and vertically from the overlying oil sands and underlying Beaverhill Lake Formation in response to the gradient. Any depressurization scheme should address the magnitudes of these flows in order to plan adequately a dewatering system. Large volumes of water will have to be pumped from the ground and subsequently transmitted by surface systems to suitable disposal. The high permeability of the basal McMurray aquifer in conjunction with the high hydraulic gradients established will mean that the entire system will have to be very reliable. Flooded pits and mine slope collapses could develop rapidly after a shutdown of the system.

This area has significant amounts of oil sand occurring below the level of the Athabasca River. This, in conjunction with the excellent basal McMurray aquifer, will result in induced infiltration from the river. Essentially, the river will act as a line source of constant hydraulic potential of about 750 ft (229 m). If mining were to take place close to the river pressure heads would have to be lowered to about 600 ft (183 m) *(Figure 15)*. Given the known hydraulic conductivities and a mine face 5,000 ft long

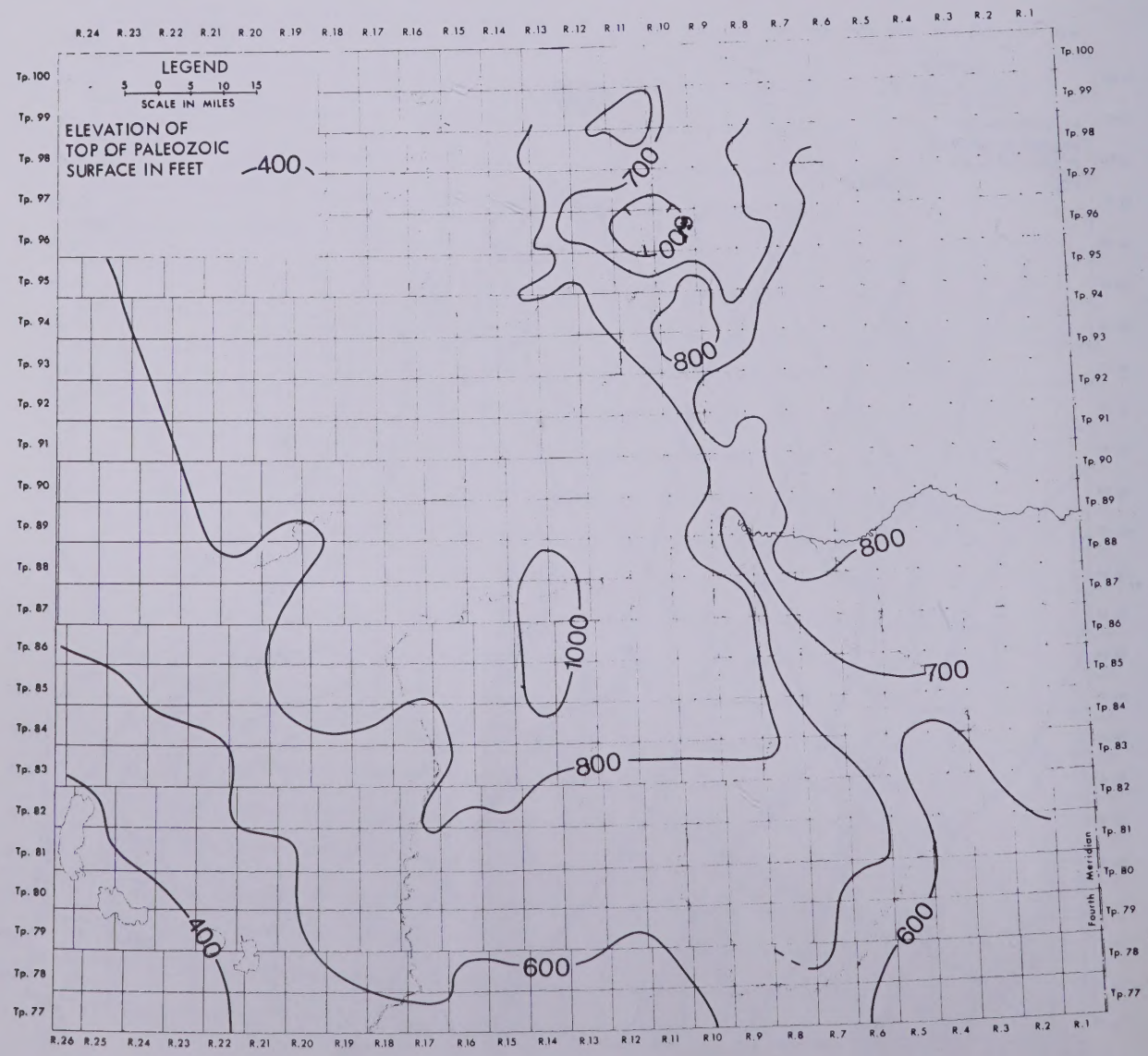


Figure 9. Structure on the top of the Paleozoic surface.

located one mile from the river, for example, up to several thousand imperial gallons per minute (70 to 140 1/sec) might be induced to flow into the well system from the river alone. Throughout the entire life of the mine induced infiltration would take place from the river to the pit. The volume of induced infiltration will vary directly with the proximity of the wells to the river.

Considering the above circumstances it might prove economically feasible to grout the basal aquifer between the mine pit and the river or to construct a cut-off wall at the bottom of an opening cut close to the river. This would serve to reduce the volume of induced infiltration. The extra cost, amortized over the life of the mine, might well be offset by the decreased pumping costs. Detailed consideration of the effects of induced infiltration in the basal McMurray aquifer should be made a part of any mine plan at an early stage.

The total dissolved solids concentration of water produced from the basal McMurray aquifer in this area is expected to be less than 10,000 mg/l. However, long-term depressurization activities may induce movement of the more saline water from the underlying formations into the pumping wells. It appears that the Beaverhill Lake Formation may have significant permeability in this area. Evidence indicating this was observed during pump tests for Home Oil Company, Tenneco Exploration, Shell Canada (Al-

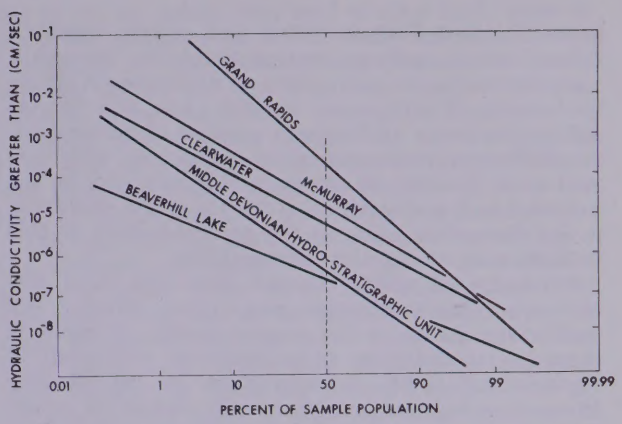


Figure 10. Frequency distribution of hydraulic conductivity for selected formations.

Figure 11. Freshwater heads: Clearwater Formation.

berta Research Council, 1976) and at two Research Council sites. Leakage upward from the Beaverhill Lake Formation is likely through fractures. Whether the volume of this poorer quality water will be significant in terms of the large volumes of better quality McMurray water cannot be determined with current data. The critical factor in this case may be the existence and permeability of fractures and sink holes in the Beaverhill Lake, as the general matrix of this formation is of very low permeability.

Discharge of water pumped from the basal McMurray or the overburden into surface streams will result in a decline in the general quality of water in those bodies. Addition of groundwater will result in higher total solids concentrations in the Muskeg River — actual concentrations will depend on pumping volumes, stream discharge, pumping water quality and quality of river water.

Water having 5,000 to 10,000 mg/l total dissolved solids can be expected in the Beaverhill Lake Formation. Concentrations of up to 100,000 mg/l are predicted in the Middle Devonian Hydrostratigraphic Unit along the western boundary of the area.

Hydrogen sulfide and methane gases are common in the basal McMurray aquifer in this area. Volumes of these gases produced from depressurization wells will likely be large enough to present a safety hazard. Surface equipment will probably be necessary to collect and dispose of the gases.

Dewatering of glacial materials may present a significant problem in the Muskeg River Area. Bayrock (1971) shows that large portions of the Muskeg River Area are covered with outwash sand and ice-contact deposits. These coarse-grained deposits tend to be quite permeable and may contain large amounts of water. This type of material, in addition, is not handled easily when water saturated. A network of ditches might be appropriate as they could work continuously to drain the glacial material and could also be utilized to carry water from the depressurizing wells in the basal McMurray aquifer.

The anticipated total dissolved solids content of water in the glacial deposits of the area is less than 1,000 mg/l. Chloride is expected to be less than about 50 mg/l. No hydrogen sulfide gas is expected. Important hydrogeological points relating to this area are summarized in *Table 2*. It is generally concluded that groundwater will play a very important role in

Figure 12. Freshwater heads: McMurray Formation.

ining of the area. Mine planning should include ydrogeological considerations at the earliest date.

Ells River Area

That portion of the mineable area herein designated s the Ells River Area is presented on *Figure 17*.

Borehole information shows that the basal McMurray aquifer is more sporadically developed in this rea. Transmissivities of the aquifer, in general, tend o be lower than in the Muskeg River Area. Depressurizing activities will doubtless be required and it vill probably be necessary to install a large number f low-capacity wells to achieve the desired drawdown f the pressure surface. The sporadic occurrence of he basal McMurray aquifer will mean that the distribution of that unit should be satisfactorily documented. Once the distribution of the aquifer is known he depressurization program can be adequately planned.

Some mining in this area will be significantly below the level of the Athabasca River. The Bitumount Basin extends into this area in Tp 96, Rs 11 and 12 (*Figure 9*). Depths of mining activity may be over 200 ft (61 m) below river level at sites fairly close to the river. Grouting or cut-off walls may have to be considered at this location also. Dewatering wells between the pit and the river may have to be completed so as to accept water from all permeable units, including barren zones within the oil sand, from river level to just below the depth of mining. Otherwise excessive pressures may be transmitted from the river to the pit face with a resulting loss of stability.

The base level of mining activities in the northern and southern portions of the Ells River Area will be generally above river level. Infiltration from the Athabasca River will not be induced. Pressures in the basal McMurray will be lower than where it lies below river level. While this would seem to imply lower dewatering costs, the discontinuous nature of the aquifer will mean a relatively large number of wells will be necessary to effect a general pressure decrease.

Mining plans that take advantage of the natural drainage of the basal McMurray at the river valley will experience cost savings over plans which work at odds with it. A mining operation moving away from the river valley and mining above river level may have little, if any, depressurization costs, as is the case at GCOS.

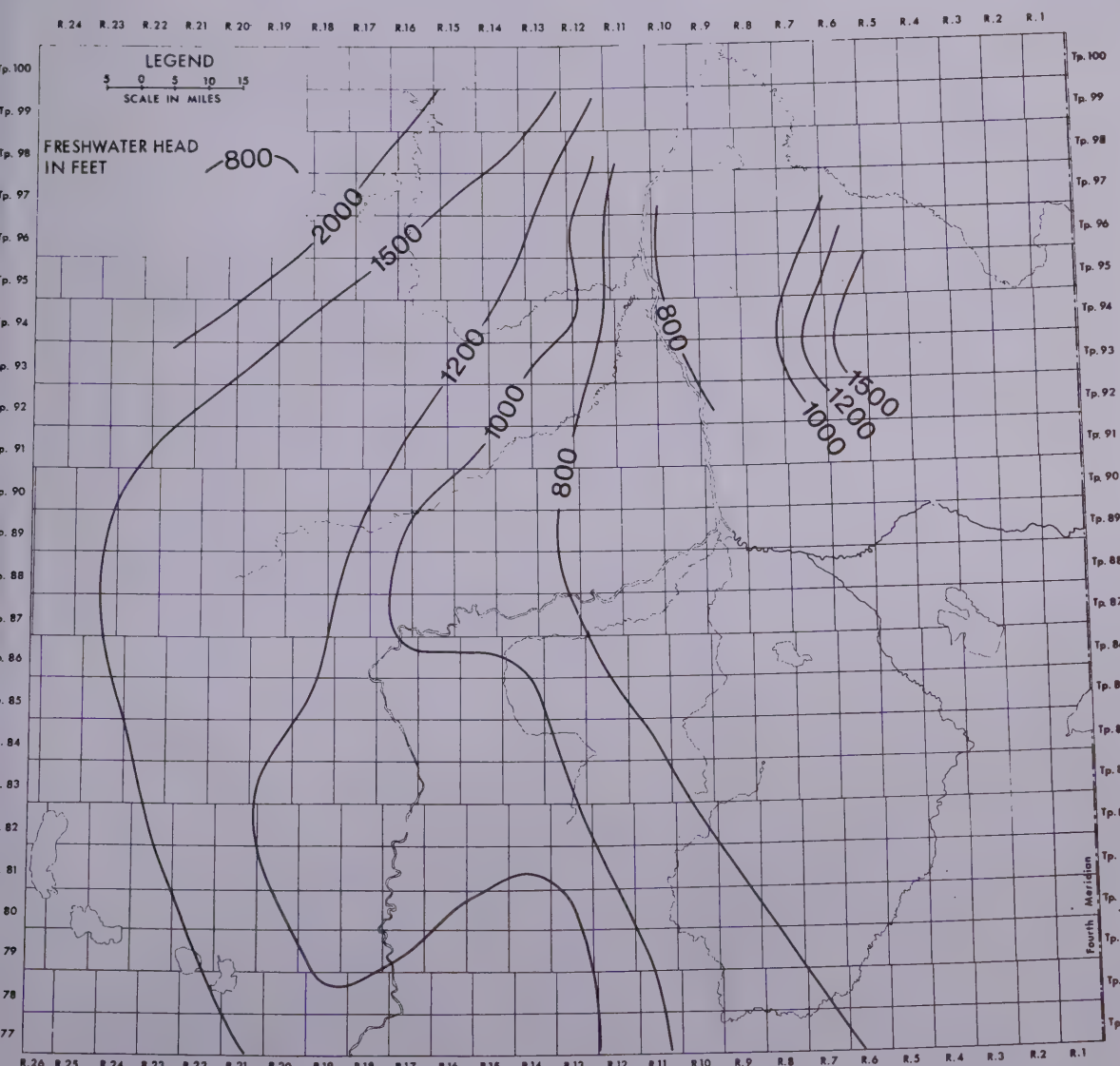


Figure 13. Freshwater heads: Upper Devonian Hydrostratigraphic Unit.

Dewatering of overburden is not expected to present a major problem in this area, however it will be necessary. The proximity of the Athabasca River and the entrenchment of such minor tributaries as the Ells and Tar Rivers will facilitate ditch drainage. Ditches of suitable gradient can be constructed because of the adjacent lowlands.

Samples of water from the basal McMurray aquifer in this area have total dissolved solids in excess of 20,000 mg/l and as high as 270,000 mg/l. This enclave of very poor quality water extends through the Upper and Middle Devonian Hydrostratigraphic Units and therefore any induced flow from depth will also be of similar quality. It seems apparent that another method of disposal of pumped water other than release into surface streams will be necessary.

The pressure ridge method (Todd, 1959; Sheahan, 1977) for control of salt water intrusion has been used successfully at various locations — consideration should be made of its application to this area. The method involves the injection of freshwater into an aquifer to cut off a source of undesirable water. The application of this method to oil sand depressurization is presented in *Figure 18*. The object of the scheme is to produce water of low total dissolved solids content which can either be reinjected or released into surface water. Utilization of the technique will involve a detailed hydrogeological feasibility study as well as an economic assessment of the various alternatives for disposal or storage of the saline water.

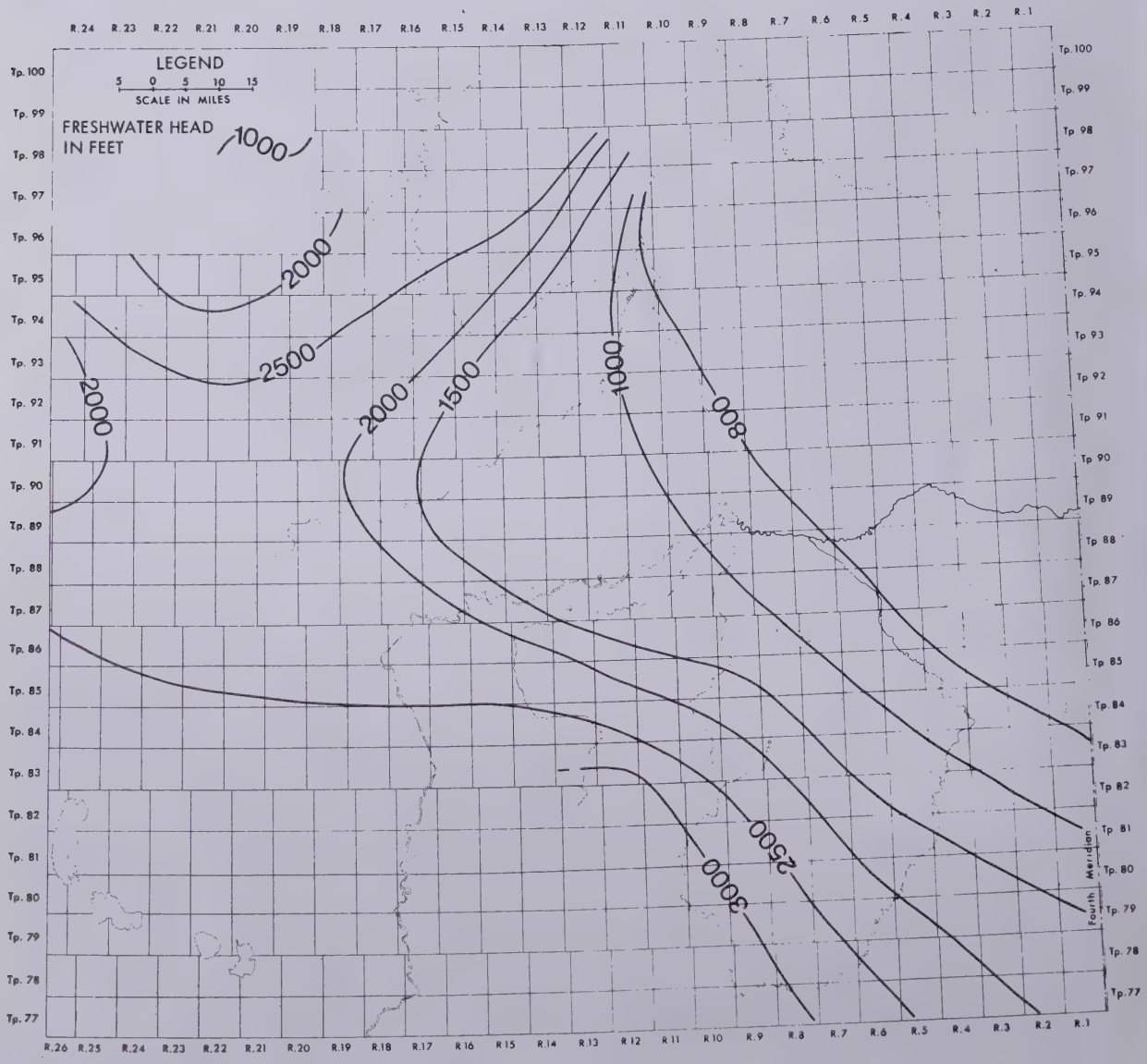
Natural gas has been observed in the McMurray Formation in this area. The volume involved is not economically significant, however, it may present safety problems. Hydrogen sulfide was quite noticeable during a pumping test of the basal McMurray in Tp 95, R 12. It therefore appears that this gas is sporadically present in the basal McMurray in the Ells River Area.

Hydrogeological problems of the area are summarized in *Table 2.*

Figure 14. Freshwater Heads: Middle Devonian Hydrostratigraphic Unit.

Mildred Lake Area

That portion of the mineable area of the Oil Sands herein designated as the Mildred Lake Area is shown on *Figure 17*. The two currently active mining projects, Great Canadian Oil Sands (GCOS) and Syncrude are located in this area.



Factor	Muskeg River Area	Ells River Area	Mildred Lake Area
Dewatering:			
Overburden	yes	minor	minor
Basal McMurray	yes	yes	yes
Infiltration from Athabasca River	yes	Bitumount Basin	no
Water Quality: (Total dissolved solids)			
Overburden	<1,000 mg/l	<10,000 mg/l	<5,000 mg/l
McMurray Formation	<10,000 mg/l	10,000 to 300,000 mg/l	<10,000 mg/l
Beaverhill Lake Formation	<10,000 mg/l	5,000 to 200,000 mg/l	<10,000 mg/l
Gases:			
H_2S	yes	possibly	minor
Other	yes	yes	possibly

Table 2. Hydrogeological factors within the surface mineable area.

The basal McMurray aquifers are sporadically developed in this area with a tendency to be slightly less permeable than in areas to the north and east. The Devonian surface is generally well above river level. This combination means that mining operations working away from the valley rim will not need elaborate depressurizing systems, as the natural and subsequent induced drainage into the pit will act to keep hydraulic heads low. This is the case at the GCOS operation.

Mining sites located away from the river valley will require depressurizing of the basal McMurray — this is the case at the Syncrude site. An extensive dewatering system is planned for this operation. The total number of wells necessary over the entire life of the mine is not available, however, in 1975 (Cary, 1975) 95 wells were planned to dewater the opening cut alone.

The installation, operation and maintenance of a dewatering system represents a continuing cost in oil sand production. This cost can be reduced significantly in the Mildred Lake Area if mining plans can be developed that take advantage of the natural draining of the system.

Dewatering of overburden materials is not expected to be a major problem in this area. The small amount of overburden dewatering necessary can be accomplished by an efficient network of ditches at the surface which could act to remove rainfall and snowmelt before it can infiltrate. The net effect of this drainage will be a lowering of water levels in near-surface aquifers.

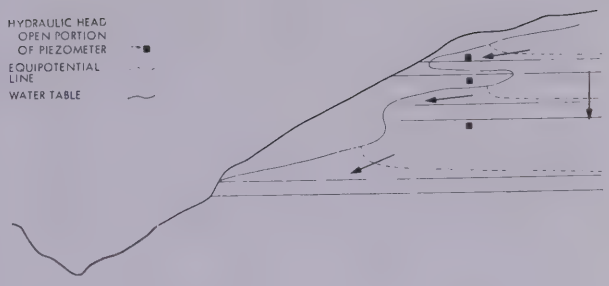


Figure 16. Unsaturated/saturated flow regime.

Water in the McMurray Formation can be expected to have less than 5,000 mg/l total dissolved solids on the west side of the Athabasca River and less than about 10,000 mg/l on the east. Discharge of water pumped to depressurize the basal McMurray aquifers will result in a decline in the quality of streamflow from the area.

Water in the Beaverhill Lake Formation generally can be expected to have slightly higher total dissolved solids than the McMurray. Concentrations up to about 10,000 mg/l may be expected in this unit. Total dissolved solids in the Middle Devonian Hydrostratigraphic Unit can be expected to be about 100,000 to 200,000 mg/l.

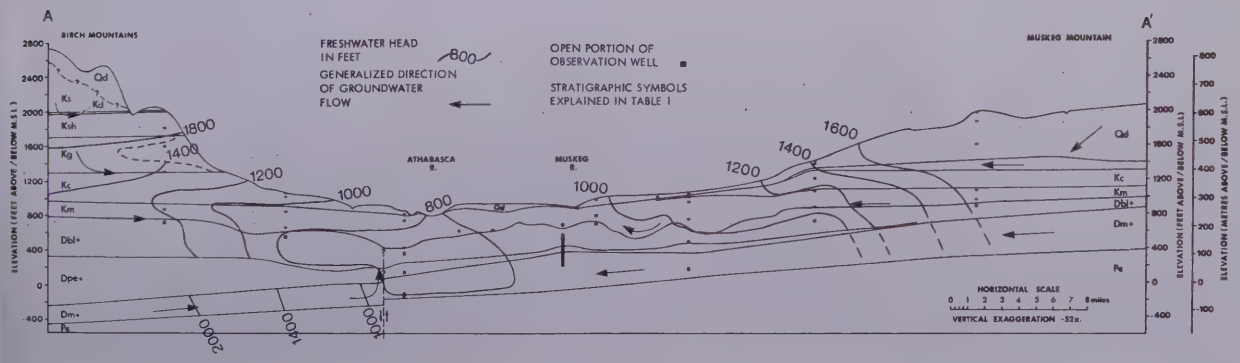
Freshwater heads in the Upper Devonian Hydrostratigraphic Unit *(Figure 13)* are about at the top of the Devonian surface *(Figure 9)*. Depressurization activities in this area will lower heads in the basal McMurray but they obviously will be higher, even during these activities, than the hydraulic head in the underlying Beaverhill Lake Formation. Under these conditions it is not anticipated that the saline water at depth will move toward the pumping wells.

Dissolved gases have been reported by Nichols (1975) to be present in the basal McMurray aquifers at the Syncrude site. The dissolved gas apparently is exsolving within the formation and reducing the permeability as hydraulic heads decline. This sort of phenomenon will have to be accounted for in any dewatering scheme as it will serve to increase the number of wells required to achieve a desired pressure reduction.

Relatively large amounts of sweet natural gas are produced from an observation well completed in Clearwater sand in TP 92, R 12, just west of the Mildred Lake Area. It is possible, therefore, that gas will be encountered in the Clearwater Formation elsewhere in the western portions of this area.

Hydrogeological factors for the Mildred Lake Area are summarized in *Table 2*.

Figure 15. Hydrogeological cross section A-A'.



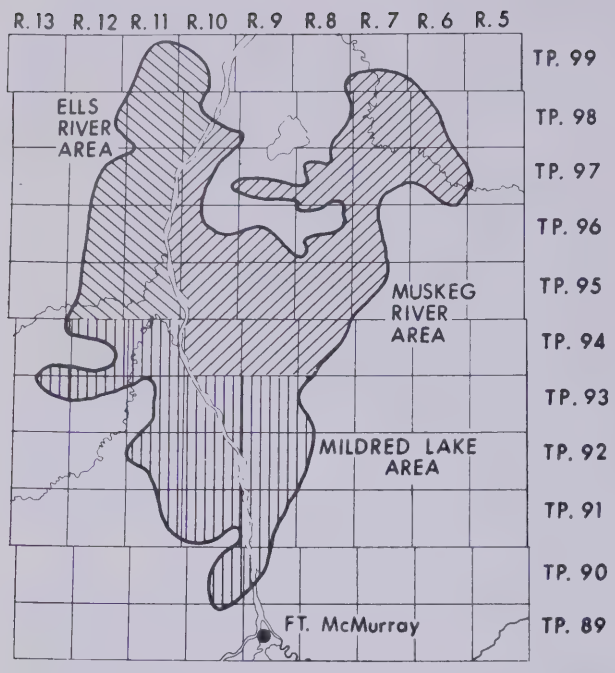


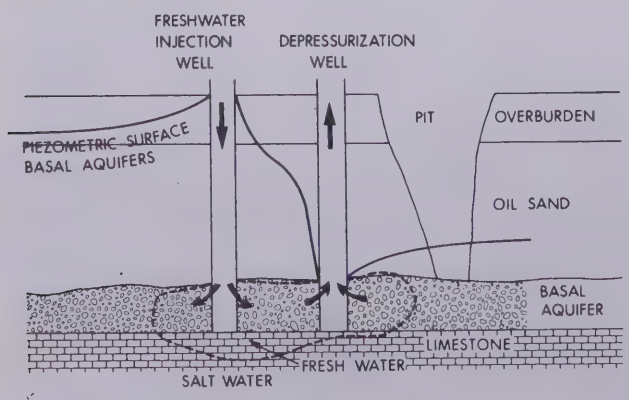
Figure 17. Hydrogeological subdivisions of the surface mineable area.

SUBSURFACE WASTE INJECTION

Geological considerations for wastewater injection in the study area were made according to many of the recommendations expressed by van Everdingen and Freeze (1971) and van Everdingen (1974a, 1974b). These considerations are of a general nature due to the lack of information regarding quality and quantity of waste waters produced from bitumen upgrading processes. The study area can be considered as having *possibly suitable* to *unsuitable* conditions for subsurface injection of liquid waste *(Figure 19)*. It is suggested that injection be limited to fluids which cannot be disposed of by any other means.

The three areas designated on *Figure 19* were selected on the basis of a combination of structural and stratigraphic factors relating to the competency of the necessary overlying confining layers. Generally the northeastern half of the area is regarded as having *unsuitable* conditions for waste injection into any formation. The southwestern half of the area has potentially suitable stratigraphy and structure to allow injection into the Middle Devonian Hydrostratigraphic Unit in the east and into both the Upper and Middle Devonian Hydrostratigraphic Units in the west.

Figure 18. Pressure ridge method.



The area defined as unsuitable for waste injection was selected on the basis of the competency of the Prairie Evaporite and Beaverhill Lake Formations to act as confining layers above an injection zone in the Middle Devonian Hydrostratigraphic Unit. As has been pointed out previously, the Sewetakun Fault has affected rocks at least as young as Clearwater age. This feature has also enhanced salt solution in the Prairie Evaporite which in turn has contributed to collapse features in the Beaverhill Lake and McMurray Formations. This indicates that the ability of both the Prairie Evaporite and the Beaverhill Lake Formations to act as confining layers for injected liquids is open to question. The possibility of rapid upward movement of injected liquids to the Athabasca or Clearwater Rivers is quite great. A schematic illustration of this situation is given in *Figure 20.*

It is also of importance to note that the Prairie Evaporite is essentially absent east of the Athabasca River *(Figure 15)* and north of the Clearwater River. This fact, combined with the obvious karstification of the Beaverhill Lake in the same area *(Figure 9)*, adds to the unsuitability for liquid waste injection.

The Middle Devonian Hydrostratigraphic Unit commonly has freshwater hydraulic heads at or above land surface *(Figure 14)*. In order to inject significant volumes of liquid against heads of this nature and hydraulic conductivities such as those indicated on *Figure 10,* pressures in excess of lithostatic may have to be used and would result in hydraulic fracturing. Over much of the *unsuitable* area vertical fractures could quite easily traverse the already thin or nonexistent Prairie Evaporite and affect the Beaverhill Lake thus creating pathways for liquid movement into a system shown to be in significant communication with the surface. Horizontal fracturing would not remedy the situation because of the possibility of intersection with the fault.

Aside from the problems of hydraulic fracturing, the large increases in pressure necessary for injection might augment flow in natural salt springs that now discharge water which has been diluted to a great extent by mixing of waters from shallow and deep flow systems. An increase in pressure in the deeper systems would mean that less dilution would take place before emergence at the surface and thus the springs would not only increase in flow but also discharge water of poorer quality.

The area noted on Figure 19 as *possibly suitable* for waste injection has been divided into two subregions based upon potential receiving formations. Waste injection into the Middle Devonian Hydrostratigraphic Unit is regarded as possible only west of the line which coincides with the influence of salt solution on the Prairie Evaporite. East of the line, as stated earlier, there is significant possibility of disturbance of the overlying units. West of the line the Unit has very high total dissolved solids content, is deeply buried and has a very impermeable upper confirming layer all of which make it acceptable as an injection unit. Possible drawbacks may be the low hydraulic conductivity *(Figure 10)* and high hydraulic heads *(Figure 14)*; however, these might be overcome through hydraulic fracturing.

Waste injection into the Upper Devonian Hydrostratigraphic Unit, particularly its lower portions, may be acceptable in the southwestern half of the

area. Here the Upper Devonian is thickened by the overlap of the Woodbend Group and is deeply buried because of the regional dip. The quality of water in the Upper Devonian Hydrostratigraphic Unit is much better than in the Middle Devonian Hydrostratigraphic Unit, however, it is still less than desirable for any use. Low hydraulic heads *(Figure 13)* mean that gravity flow through the injection well may be possible if zones of significant hydraulic conductivity can be located. Because of an apparently low hydraulic conductivity it may be necessary to resort to fracturing in order to inject significant volumes of liquid. Care should be taken to insure that injection wells are properly sealed and completed significantly far below the Oil Sands to preclude migration of waste to those deposits .

SUMMARY

1. Alternating layers of relatively low and high permeability combined with high local relief result in dominantly vertical or dominantly horizontal flow directions. These conditions are characteristic of the Cretaceous Hydrostratigraphic Unit and result in a complex series of "perched" groundwater flow systems. Unsaturated conditions may extend laterally many miles into a rock unit from its subcrop or outcrop.

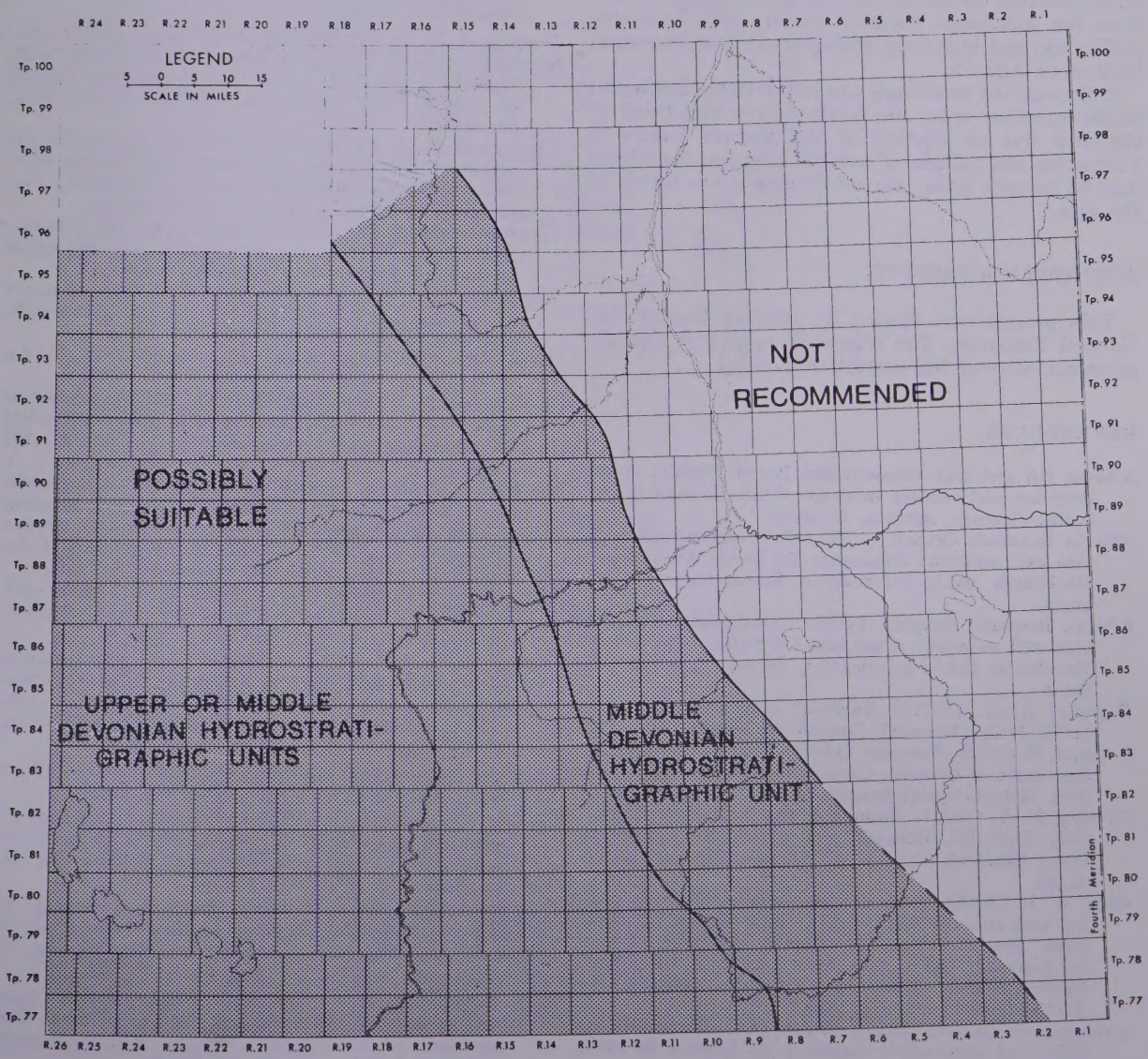
2. The Middle Devonian Hydrostratigraphic Unit underlying the Prairie Evaporite is characterized by freshwater heads commonly far in excess of those in overlying units. Flow is dominantly lateral and up dip except in the northeast quarter of the map area where the flow is mainly down dip. Strong horizontal gradients are observed near the Sewetakun Fault.

3. The Prairie Evaporite acts as a very poorly permeable confining bed in those portions of the area west of the Athabasca River or south of the Clearwater River.

4. The Upper Devonian Hydrostratigraphic Unit has strong horizontal gradients toward the Athabasca River Valley. Low hydraulic heads are widespread near the Sewetakun Fault and are the result of secondary permeability caused by collapse of the Unit into salt solution cavities.

5. The Grand Rapids Formation is the best aquifer in the area. Water quality is generally good and hydraulic conductivities average about 2.8 x 10^{-4} cm/sec.

Figure 19. Suitability for liquid waste injection.



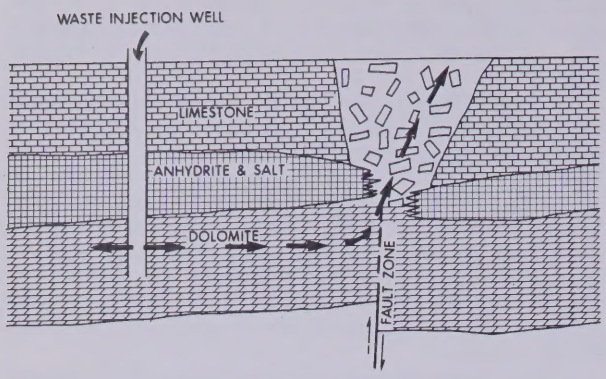


Figure 20. Movement of wastes through faulted and collapsed zone.

Low hydraulic heads and limited areal distribution will restrict usage, however.

6. The surficial mining area can be divided into three areas each having a different combination of hydrogeologic problems. One common problem will be depressurization of the basal McMurray Aquifer. More localized problems include induced infiltration from the Athabasca River to mining pits, hydrogen sulfide gas and high total dissolved solids in the basal McMurray Aquifer.

7. Subsurface conditions are not suitable for liquid waste injection under the northeastern one third of the area due to solution of the Prairie Evaporite Formation and collapse of overlying layers. Conditions may be suitable under the southwestern two thirds of the area.

ACKNOWLEDGEMENTS

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